Parameterization of Integrated Aerosol Effects In Marine Stratocumulus Clouds

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LONG-TERM GOALS

The development and improvement of cloud microphysical parameterizations for use in cloud and numerical weather prediction models

OBJECTIVES

Conduct detailed studies of marine stratocumulus cloud microphysical processes using a high-resolution large eddy simulation (LES) model with explicit microphysics. Achieve better understanding of interactions between microphysical, radiative and boundary layer thermodynamical processes in order to improve their formulation in numerical weather prediction models.

Towards this goal, we develop:

1) A new state-of-the-art version of the LES explicit microphysics model designed to run on distributed parallel computing systems and capable of simulating ensembles of convective clouds in large domains, as well as fine cloud structure to study processes entrainment and mixing in clouds.

2) Methods for retrieval of cloud and drizzle parameters for use in initialization of numerical forecast models.

3) The parameterization of drop size distributions by analytical functions for application in cloud physics parameterizations and in remote sensing algorithm development.

APPROACH

The research is based on the CIMMS high-resolution LES model with explicit formulation of aerosol and drop size-resolving microphysics. During the last year we have developed a new version of the model which can simulate not only marine boundary layer stratocumulus clouds, but also ensembles of convective clouds. The main focus of simulations with the new model is to expand our cloud microphysics parameterization for stratocumulus clouds (Khairoutdinov and Kogan 2000) for applications in models of shallow and deep convection. The LES experiments with grid sizes down to several meters, as well as observations from field projects, will be used to study the role of entrainment, drop recycling, and CCN regeneration in rain formation.

Using explicit microphysics data from the model, we conduct Observing System Simulation Experiments (OSSE), such as simulating observations from Millimeter Wave Cloud Radar (MMCR) with Doppler capabilities. These simulations are important for developing techniques for the retrieval

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of cloud liquid water and drizzle flux, both of which might be used to constrain cloud properties in mesoscale prediction models. Similarly, explicit microphysics data can be used to evaluate the potential of analytical functions to approximate drop size distributions and their moments.

WORK COMPLETED

The following tasks have been completed this year:

1. The new version of the CIMMS model with explicit formulation of cloud microphysics (SAMEX) has been developed. The model includes dynamical core from the SAM model (System for Atmospheric Modeling) developed by Dr. Marat Khairoutdinov (formerly an OU graduate student whose PhD thesis work was supported by ONR grants and who is currently a Research Scientist at CSU). The new dynamical core is capable of running on distributed parallel computing systems using the message passing interface (MPI) and allows simulations with grid sizes down to several meters, as well as simulations of ensemble of cumulus convective clouds in large computational domains.

2. Errors of cloud parameters retrievals based on radar reflectivity, radial velocity, and spectrum width have been evaluated under the controlled framework of the Observing System Simulation Experiments (OSSEs). Cloud radar parameters have been obtained from drop size distributions obtained from a synthetic dataset generated by the CIMMS LES model with size-resolved microphysics.

3. The potential of the frequently used log-normal distribution function to approximate cloud drop spectra in non-precipitating and precipitating marine stratocumulus has been evaluated.

RESULTS

1. The simulation of an ensemble of convective clouds

Using the newly developed version of the CIMMS LES model with explicit microphysics (Kogan, 1991, Kogan et al. 1995, and Khairoutdinov and Kogan 1999) we have conducted simulations of cumulus convection system based on data from the recent RICO field project (Rain in Cumulus over the Ocean). The numerical experiment was conducted in a 128x128x100 domain. The CCN distribution had a total concentration of 155 cm^{-3}, which results in concentration of cloud droplets of about 80 cm^{-3}. The current formulation of the model uses 19 CCN bins and 34 mass-doubling droplet bins that extend from 1 μ up to 2 mm. The 24 hr simulation took about 11 hrs of wall clock time using 64 processors on a Xeon64 cluster.

The results from such simulation are shown on Figure 1 below which depicts cloud drop spectra through a cross-section of a selected precipitating multi-cell cloud. Areas shaded in pink denote regions where cloud drops are actively growing, the spectra in these areas, where condensation and coagulation are particularly strong, usually display two modes corresponding to cloud and drizzle size drops.

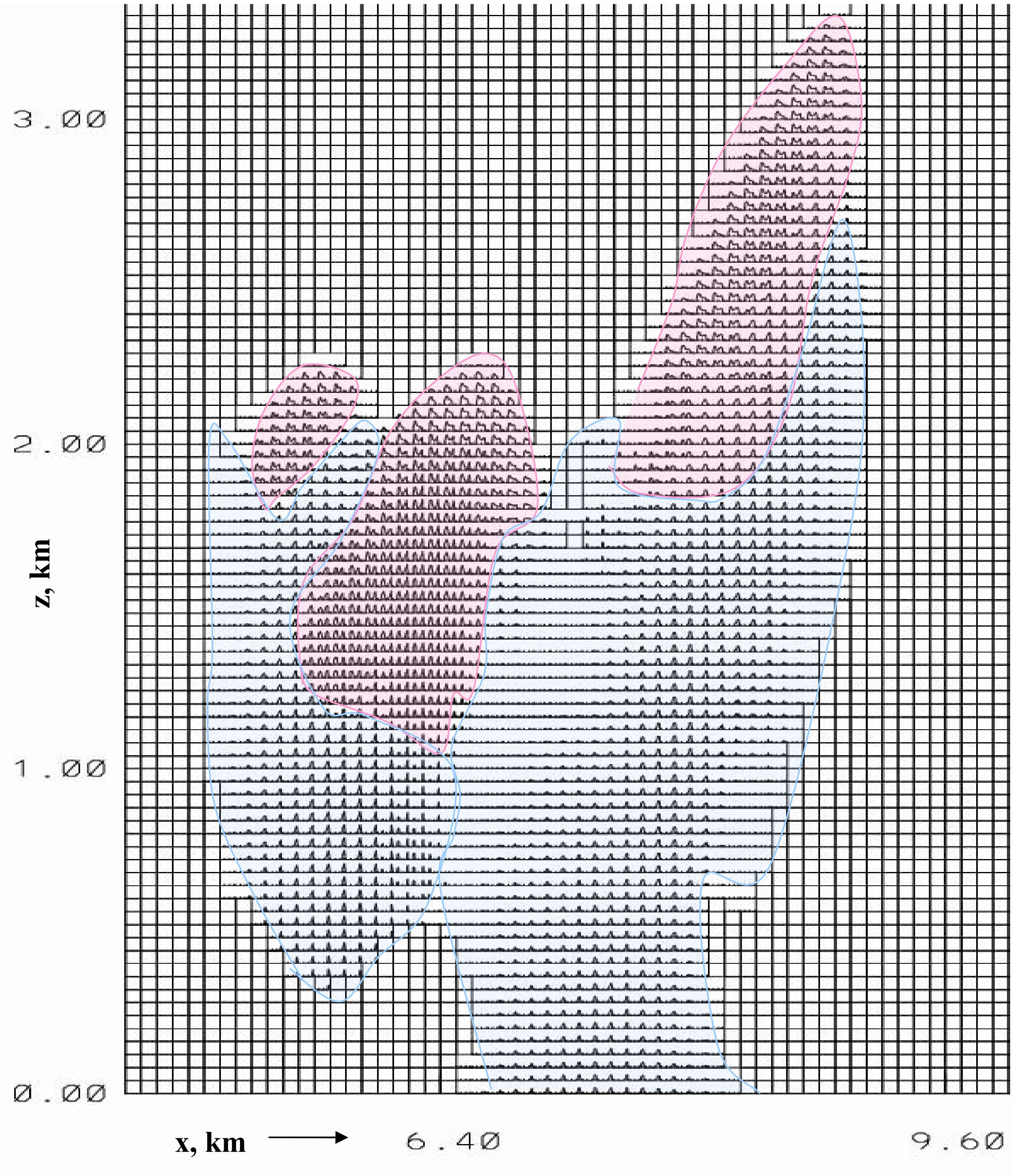

Figure 1. The cross-section of a portion of the 13×13×4 km simulation of an ensemble of convective clouds based on RICO dataset. One multi-cell cumulus cloud is shown. The small boxes at each grid point depict plots of drop mass distribution on a logarithmic scale from 1 μ to 1 mm. [graph: Pink shaded areas of active cloud growth contain predominantly bimodal drop size distribution, while blue shaded areas of evaporation and falling precipitation contain mostly unimodal rain drop distributions. Rain from the right, more mature cell reaches the surface, while rain from the left cell is confined to the subcloud layer]

The blue shaded areas denote regions of falling precipitation or evaporation on the side and between the cells. The right cell is an especially vigorous with rain reaching the ocean surface. The drop spectra from these types of simulations will be used as a data set for development of a generalized cloud physics parameterization using the methodology similar to that of Khairoutdinov and Kogan (2000).

2. The enhancement of radar retrievals by the use of higher moments of drop spectrum

Using the OSSE approach, we simulated a millimeter wavelength cloud Doppler radar and applied the simulation results for analysis of reflectivity and Doppler velocity returns from stratocumulus clouds with different amounts of precipitation. Measurements made during the Atlantic Stratocumulus Transition Experiment (ASTEX) field program in clean and polluted air masses were used to initialize the CIMMS explicit microphysics large-eddy simulation model.

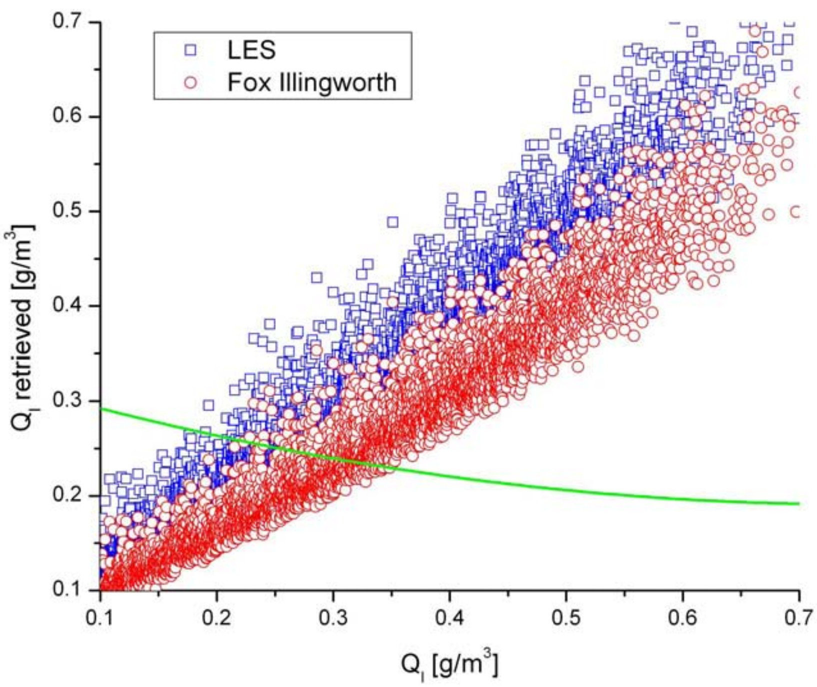

Figure 2. The comparison of liquid water retrievals based on LES data and ASTEX observations by Fox and Illingworth (1999). The green line shows the ratio of Q_l retrievals based on LES and ASTEX data. [graph: The retrieval of liquid water algorithm obtained based on LES data has an accuracy of about 20%]

Including Doppler velocity or spectrum width in retrievals of liquid water content (LWC) or precipitation flux significantly reduces retrieval errors relative to methods employing reflectivity alone. In moderate drizzle (~1 mm/day) the correlation (R^2) between retrieved LWC and observed increases from 0.756 to 0.969 when Doppler velocity is incorporated into the retrieval.

Correlation for retrieved precipitation rate improves similarly and increases from 0.794 to 0.962. Both velocity and spectrum width have approximately the same potential for improving retrieval of microphysical parameters. It has to be noted that the error estimates in this study constitute the lower bound on errors of microphysical retrievals. If the contributions to the radar moments from air

turbulence can be constrained and minimized, then the use of additional radar parameters, such as Doppler velocity or spectrum width, may contribute to substantial improvement of microphysical retrievals under a wide range of precipitation conditions (Fig. 2).

3. Parameterization of drop size distributions by log-normal analytical functions

The development and application of cloud parameterizations, as well as the development of cloud microphysics retrieval techniques, requires knowledge of drop size distributions (DSDs). Because of the large natural variability of DSD, their approximations by known analytical functions is important. We have evaluated the potential of the frequently used log-normal distribution function to approximate cloud drop spectra in non-precipitating and precipitating marine stratocumulus.

The evaluation is based on the CIMMS LES model with an explicit (size-resolving) formulation of liquid phase microphysical processes. Cloud physics processes are formulated based on prediction equations for cloud condensation nuclei and cloud/drizzle drops (19 and 25 bins, respectively) (Kogan et al 1995, and Khairoutdinov and Kogan 1999). Several cases of stratocumulus clouds observed during the Atlantic Stratocumulus Transition Experiment (ASTEX) field experiment in clean and polluted air masses have been simulated. The simulations represented cases with different intensities of drizzle *in the cloud*. From each simulation we extract several thousands DSDs that are used to calculate cloud integral moments, including drop concentration, liquid water content, rain rate, and radar reflectivity. As the log-normal distribution function is defined by three parameters, we use cloud drop concentration, 1st and 2nd moments for its definition, and compare higher moments (liquid water content, rain rate, and radar reflectivity) given by log-normal function with the moments from explicit LES derived drop spectra (Fig. 3).

Figure 3 shows that for non-precipitating clouds LWC and rain rate can be quite well approximated using the log-normal distribution function. The representation of radar reflectivity is less accurate and is in most cases overestimated due to the long tail of the log-normal distribution function. In the case of drizzling clouds, the radar reflectivity parameter is predominantly underestimated, obviously due to the fact that a single mode log-normal distribution function has little or no information on the drizzle drops far on the right from the mode. We are now exploring the possibility of improving the approximation of higher moments by the use of double mode log-normal distribution functions.

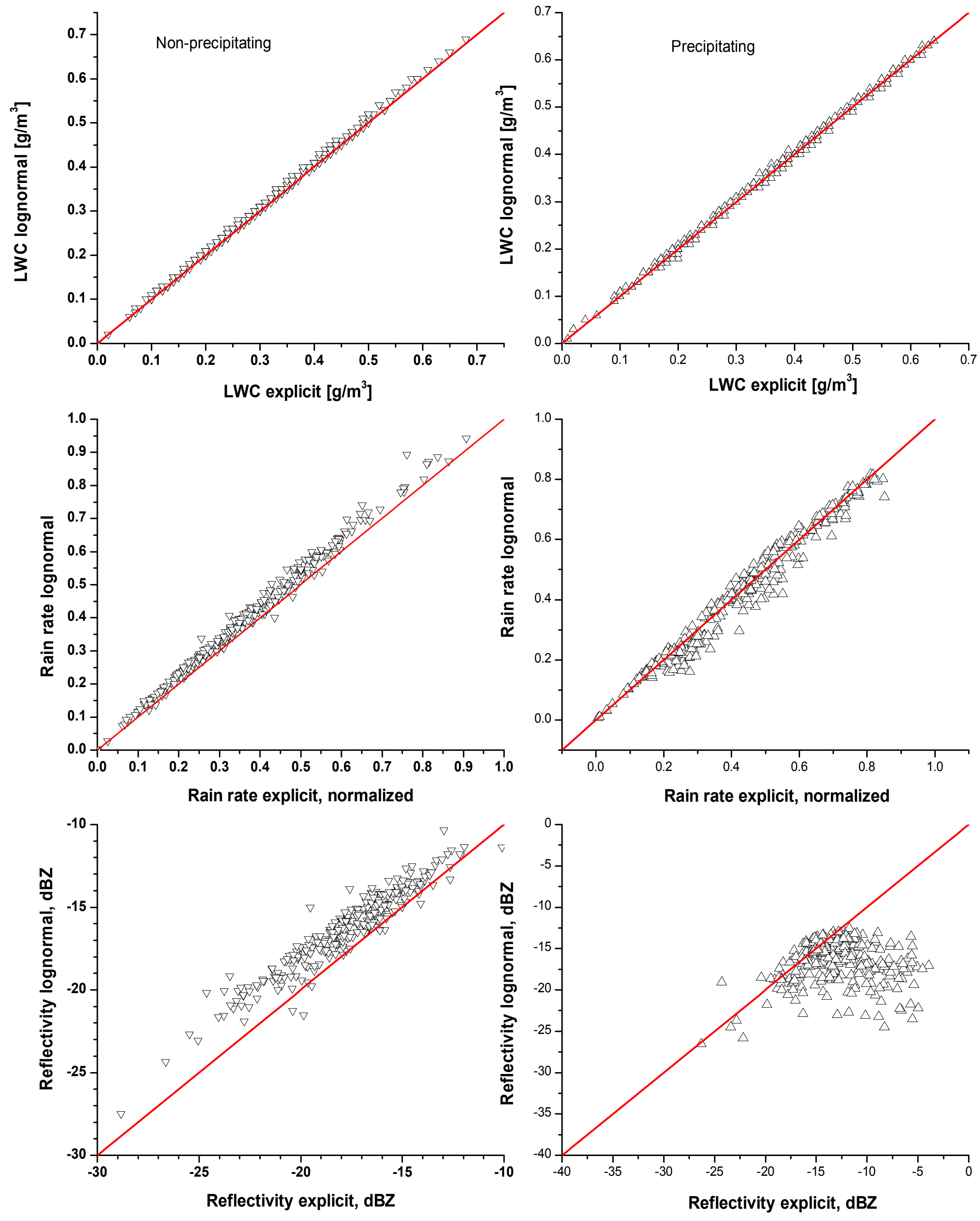

Figure 3. Scatter plots of liquid water content, rain rate, and radar reflectivity approximated the by the log-normal analytical distribution function as a function of corresponding parameters explicitly calculated from the LES derived drop spectra. Left (right) panels show plots for non-precipitating (precipitating) stratocumulus. [graph: The log-normal distribution can rather accurately approximate LWC and rain rates, but fails to represent radar reflectivity]

IMPACT

The improved parameterization of the physical processes in marine stratocumulus clouds will lead to more accurate numerical weather predictions for Navy operations. The new retrieval algorithms of cloud and drizzle parameters will allow more accurate initialization of forecast models.

TRANSITIONS

Our results have been reported at five scientific meetings, published in two major refereed journals and conference proceedings (total of 11 papers) and, thus, are known to the scientific community.

RELATED PROJECTS

The study is aimed at development of physical parameterizations for cloud and regional scale models. It is related to the ONR project "Improvement of the cloud physics formulation in the US Navy Coupled Ocean-Atmosphere Modeling Prediction System (COAMPS)" which goal is to implement physical parameterizations into mesoscale prediction models in general, and COAMPS in particular.

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